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A BEAMFORMING STUDY USING OUTPUTS FROM THE EXTENDED E3 SUBARRAY AT THE MONTANA LASA

11 September 1967

Prepared For

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A BEAMFORMING STUDY USING OUTPUTS FROM THE EXTENDED E3 SUBARRAY AT THE MONTANA LASA

SEISMIC DATA LABORATORY REPORT NO. 198

AFTAC Project No.:	VELA T/6702
Project Title:	Seismic Data Laboratory
ARPA Order No.:	624
ARPA Program Code No.:	5810
Name of Contractor:	TELEDYNE, INC.
Contract No.:	F 33657-67-C-1313
Date of Contract:	2 March 1967
Amount of Contract:	$1,736,617
Contract Expiration Date:	1 March 1968
Project Manager:	William C. Dean (703) 836-7644

P. O. Box 334, Alexandria, Virginia

AVAILABILITY

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This research was supported by the Advanced Research Projects Agency, Nuclear Test Detection Office, under Project VELA-UNIFORM and accomplished under the technical direction of the Air Force Technical Applications Center under Contract F 33657-67-C-1313.

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TABLE OF CONTENTS

	Page No.
ABSTRACT	
INTRODUCTION	1
PROCEDURE	2
Beamforming	2
Zero-lag Correlations	3
Signal, Noise, and Signal-to-Noise Ratio	6
RESULTS	7
CONCLUSIONS	9
REFERENCES	10

LIST OF ILLUSTRATIONS

		Follows Page No.
Figure 1.	LASA Extended E3 Subarray	1
Table 1.	The Extended E3 Subarray	1
Table 2.	Source Data	1
Table 3.	Sensor Groups and Spacing for N=6	2
Table 4.	Sensor Groups and Spacing for N=3	2
Table 5.	Sensor Groups and Spacing for N=7	2
Figure 2.	Noise Reduction for N=3	5
Figure 3.	Average Noise Reduction by Beamforming	6
Figure 4.	Average S/N Gain by Beamforming	6
Figure 5.	Average Noise Reduction by Beamforming Six Outputs of the Extended E3 Subarray	6
Figure 6.	Average S/N Gain By Beamforming Six Outputs of the Extended E3 Subarray	6
Figure 7.	Average Noise Reduction in the Extended E3 Subarray for Two Experimental Methods	6
Figure 8.	Average Noise Reduction in the Extended E3 Subarray for Two Experimental Methods	8

ABSTRACT

Short-period seismograms representing nine teleseismic earthquakes recorded by vertical component instruments in the extended E3 subarray at the Montana LASA were bandpass-filtered and beam-formed to determine the effect on average input signal-to-noise ratio, signal, and noise.

Results of the study show that beamsteering all 25 outputs (prefiltered 0.4-3.0 cps) from the extended E3 subarray fails to improve the signal-to-noise by the square root of N, where N is the number of inputs to the beams. This is due partly to the fact that noise is in some measure correlated between the more closely spaced sensors and therefore is not reduced by $N^{1/2}$, and partly to signal losses (1-2 db) accompanying the beam-forming process.

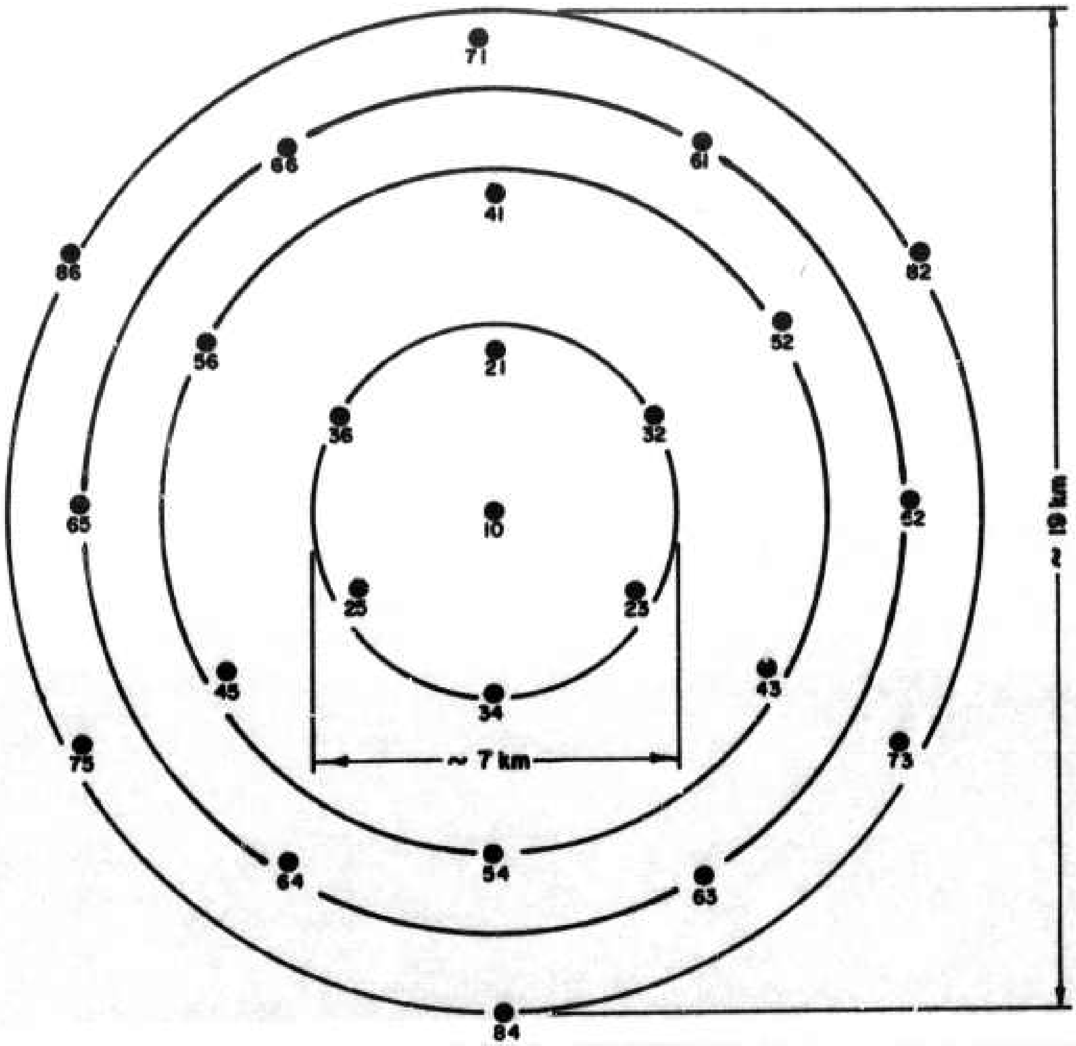
The analysis further indicates that beams consisting of 3, 6, and 7 input traces prefiltered 0.4-3.0 cps reduce rms noise levels at the subarray by approximately $N^{1/2}$ at a minimum inter-sensor spacing equal to or greater than 6 kilometers. Finally, if the input data are prefiltered to the band 0.6-2.0 cps, the minimum spacing for $N^{1/2}$ noise reduction is decreased to about 5 kilometers.

INTRODUCTION

This analysis was undertaken in support of the Vela Seismological Center's effort to evaluate the performance of the extended E3 subarray at the Large Aperture Seismic Array in Montana, and to determine the minimum spacing for short-period LASA subarray elements for which beamforming reduces the rms noise level by $N^{\frac{1}{2}}$. We are concerned with signal loss, rms noise reduction, noise power reduction at 1 cps, and signal-to-noise ratio gain, resulting from prefiltering and beamsteering various combinations of outputs.

The data used in this study are nighttime recordings, made by sensors in the E3 subarray, of nine teleseismic earthquakes which occurred over a two month period, January-March 1967. We refer to the enlarged E3 subarray which has been in operation since December 1966. This subarray has a diameter of ~ 19 kilometers, and contains 25 sensors with spacings $\geq$ 3 kilometers, as shown in Figure 1. Additional information pertinent to sensor locations, azimuths, and projections is listed in Table 1. The source data shown in Table 2 were taken from P. D. E. cards furnished by the USC&GS.

In this study data were reduced by detrending all seismograms and by correcting for system magnification at 1 cps to convert digital counts to millimicrons (mμ) ground displacement. The data were further prepared for beamforming by prefiltering using two recursive bandpass filters, independent of one another, to eliminate noise frequencies lying well outside the passband of the signal, i.e., long-period microseisms and frequencies greater than 2-3 cps. Outputs from each filter were beamsteered automatically, by computer, using the assumed apparent phase velocity and back azimuth (station-to-epicenter) shown in Table 2.



INNER CIRCLE REPRESENTS SIZE OF ORIGINAL E3

Figure 1. LASA Extended E3 Subarray

Sensor No.	Latitude	Longitude	Elevation (meters)	Azimuth (degrees from N)	Projections From Center (km)	
					X(E/W)	Y(N/S)
10	46°08'58"	106°20'03"	913.3			
21	46°10'35"	106°20'07"	895.2	358.5378	- .0764	2.9949
41	46°12'12"	106°20'10"	853.6	358.5443	- .1519	5.9779
61	46°12'45"	106°17'04"	867.5	28.6257	3.8215	7.0032
71	46°13'48"	106°20'24"	782.1	357.1646	- .4428	8.9414
32	46°09'57"	106°1-'44"	853.1	58.5959	2.9697	1.8138
52	46°10'57"	106°15'52"	852.2	55.5633	5.3762	3.6877
62	46°09'07"	106°13'51"	909.8	87.9708	7.9698	.2847
82	46°11'41"	106°13'47"	905.2	58.0592	8.0546	5.0236
23	46°08'11"	106°18'00"	894.0	118.5899	2.6372	-1.4380
43	46°07'25"	106°15'57"	875.1	118.5378	5.2738	-2.8693
63	46°05'16"	106°16'48"	916.5	148.7195	4.1637	-6.8549
73	46°06'39"	106°13'56"	880.0	118.5575	7.8723	-4.2866
34	46°07'05"	106°19'59"	918.4	178.6054	.0852	-3.5006
54	46°05'28"	106°19'55"	963.3	178.5502	.1643	-6.4946
64	46°05'19"	106°23'01"	868.2	209.5283	-3.8215	-6.7483
84	46°03'49"	106°19'45"	921.6	177.7222	.3793	-9.5374
25	46°08'07"	106°22'02"	927.2	238.5916	-2.5579	-1.5625
45	46°07'16"	106°24'02"	898.2	238.5159	-5.1171	-3.1352
65	46°11'00"	106°26'14"	848.1	270.4701	-7.9422	.0675
75	46°06'32"	106°26'10"	823.8	240.1544	-7.8477	-4.5048
36	46°09'52"	106°22'26"	928.8	298.5786	-3.0706	1.6735
56	46°10'41"	106°24'32"	963.8	298.9519	-5.7572	3.1865
66	46°12'40"	106°23'39"	873.4	328.9079	-4.1330	6.3552
86	46°11'33"	106°26'31"	918.0	299.9851	-8.2907	4.7859

Table 1. The Extended E3 Subarray

Event Name	Date	Origin Time	Location			Distance	
			Lat.	Long.		DEG	KM
HONSHU	02 Mar 67	08:17:44.5	35.7 N	139.9 E		79.1	8793
KURILE	05 Mar 67	09:55:15.0	46.8 N	152.7 E		64.4	7165
NORTH PACIFIC	08 Mar 67	05:13:34.0	24.4 N	142.8 E		86.0	9564
HONSHU	10 Mar 67	01:54:17.5	32.4 N	137.7 E		82.8	9204
NORTH ATLANTIC	11 Mar 67	03:05:24.0	55.9 N	34.5 W		44.3	4923
HOKKAIDO	17 Mar 67	02:22:37.9	42.0 N	142.5 E		73.0	8119
FOX	17 Mar 67	06:47:40.9	53.6 N	165.3 W		37.5	4170
JUJUY	17 Mar 67	11:17:19.0	21.2 S	67.7 W		75.6	8408
SHIKOKU	19 Mar 67	02:54:22.4	28.0 N	130.5 E		90.0	10012

Depth in KM	Apparent Velocity	Back Azimuth	Cal Date	USC & GS Mag
75	20.3	310.7	11 Jan 67	4.6
33	16.9	311.6	11 Jan 67	4.4
33	22.3	301.4	11 Jan 67	4.5
377	21.2	309.9	11 Jan 67	4.4
33	13.9	50.1	11 Jan 67	4.7
57	19.0	313.4	11 Jan 67	4.7
44	13.1	303.0	11 Jan 67	4.4
189	19.6	143.0	11 Jan 67	4.2
48	23.2	312.3	11 Jan 67	4.9

Table 2. Source Data

PROCEDURE

The short-period seismograms used in this analysis were recorded by vertical-component LASA sensors which produce upward trace deflection corresponding to upward ground motion at the recording site. All outputs were bandlimited either in the range 0.4-3.0 cps or 0.6-2.0 cps, using 4-Pole Butterworth recursive filters whose amplitude responses were described by Flinn et al, (1966).

Beamforming

Two procedures were used in selecting data to be beamformed. Our objective in the first was to evaluate the performance of the extended array, and we concerned ourselves with varying the number of inputs, N, to a beam as opposed to evaluating the effect of inter-sensor spacing, Δ. Beams were formed on P arrivals using data prefiltered to the band 0.4-3.0 cps for N equal to 6, 12, 13, 18, 19, and 25. These correspond to traces recorded in the outer (or inner) ring, outer 2 rings, inner two rings plus the center, outer 3 rings, inner three rings plus the center, and the entire subarray. We have already pointed out that a uniform distribution of sensors was not considered in beamsteering these data. Consequently, it follows that about the only meaningful reference to spacing is relative to the minimum separation of sensors contributing to the beams; these values (in kilometers) corresponding to the beams discussed above are 9.5 or 3 (outer ring or inner ring, respectively), 4.7, 3, 3, 3, and 3.

A similar procedure was used for each of nine events to determine the average effect of a variable number of beam inputs (N) on signal loss, rms noise reduction, noise power reduction at 1 cps, and signal-to-noise ratio enhancement, each quantity being referred to a mean taken from the input traces.

Contributing Sensors	~Circumferential Spacing (km)			
	3*	6*	8*	9*
	21	41	61	71
	32	52	62	82
	23	43	63	73
	34	54	64	84
	25	45	65	75
	36	56	66	86

* Plots Are Averages Taken Over Seven Events

Table 3. Sensor Groups and Spacing for N=6

	Spacing (km)							
Contributing Sensors	3*	4*	6*	8*	9*	10**	14**	16**
	10 21 36	54 63 64	10 41 56	10 63 64	10 71 86	52 54 56	62 64 66	71 73 75
	10 21 32	43 62 63	10 41 52	10 62 63	10 71 82	41 43 45	61 63 65	82 84 86
	10 23 32	52 61 62	10 43 52	10 61 62	10 73 82			
	10 23 34	41 61 66	10 43 54	10 61 66	10 73 84			
	10 25 34	56 65 66	10 45 54	10 65 66	10 75 84			
	10 25 36	45 64 65	10 45 56	10 64 65	10 75 86			

*Plots Are Averages Taken Over six Beams

** Plots Are Averages Taken Over Two Beams

Table 4. Sensor Groups and Spacing for N=3

	Spacing (km)			
	3	6	8	9
Contributing Sensors	10	10	10	10
	21	41	61	71
	32	52	62	82
	23	43	63	73
	34	54	64	84
	25	45	65	75
	36	56	66	86

Table 5. Sensor Groups and Spacing for N=7

Table 3 lists four sets of traces contributing to beams containing six inputs each (N=6), where each set represents traces recorded on an individual ring of the subarray. This procedure was our first attempt at holding N constant and varying Δ, in this instance a circumferential measurement. Seven of the original nine events were used to obtain average values. The procedures discussed thus far were extended to include power spectra based on individual channels and sum traces. Spectral estimates were computed over 60 seconds of noise (1200 digital points) using 120 lags.

In the second part of the study we used seismograms recorded during the night of 17 March 1967 to establish a relationship between inter-sensor spacing and noise reduction. Two experimental methods were used to determine noise reduction by beaming either three or seven traces; the first method relied on the zero lag autocorrelations and cross-correlations as described in the following section, while the second consisted of trace summation. In the case of N=3, uniform sensor spacings of 3, 4, 6, 8, 9, 10, 14, and 16 kilometers were used and for N=7 separations of 3, 6, 8, and 9 kilometers were employed. Solutions were obtained for data limited to the band 0.4-3.0 cps after which we repeated the process with traces prefiltered to 0.6-2.0 cps.

In Tables 4 and 5 we have listed sensors which contributed to 3-element and 7-element beams respectively. As shown in Table 4, outputs from either 2 or 6 beams were used to compute average noise reduction values. Referring to Table 5, we note that only one beam for each spacing was used to describe noise behavior.

Zero-lag correlations

The reduction in noise due to straight summing is based on the assumption that the data trace at each location in the E3 subarray consists of a zero-mean, stationary-noise process with a cross-correlation function given by

$$E[n_k(t)n_\ell(t')] = R_{k\ell}(t-t') \tag{1}$$

Under these conditions it can be shown that the noise reduction due to summing can be expressed as

$$R = -10[\log N - \log\{1 + (N-1)\tilde{\rho}\}] \tag{2}$$

where $\tilde{\rho} = \bar{M}/\bar{N}^2$ is the ratio of the average zero-lag cross-correlation. Hence

$$\bar{M} = \frac{\sum_{k\neq\ell} R_{k\ell}(0)}{N(N-1)}, \quad \bar{N}^2 = \frac{\sum_{k} R_{kk}(0)}{N} \tag{3}$$

This equation is the direct time domain equivalent of that used by Capon et al. (1967) in the frequency domain, and can be interpreted as the reduction over the entire band of interest. In this report, this band is either (0.4-3.0 cps) or (0.6-2.0 cps), since the data are prefiltered to either one of these two bands. Now, examining equation (2) shows that if $\tilde{\rho} = 0$ the reduction is -10 log N which is the $(N)^{1/2}$ value expected with uncorrelated noise, however, if $\tilde{\rho}$ is negative, then one may expect on certain occasions to have noise reductions exceeding $(N)^{1/2}$.

In the computational procedure for an array of N elements, we shall present the sample estimates for the reduction which are calculated from the estimated zero-lag auto-correlation and cross-correlation functions

$$\hat{R}_{k\ell}(0) = \frac{1}{T}\int_0^T n_k(t)n_\ell(t)\,dt, \quad k,\ell = 1,\ldots,N \tag{4}$$

If the estimated reduction is $\hat{R}$ and the estimated value of the parameter $\tilde{\rho}$ is $\tilde{r}$ then the sample reduction is written as

$$\hat{R} = -10[\log N - \log\{1+(N-1)\tilde{r}\}] \tag{5}$$

It is experimentally observed that the cross-correlations between sensors in the E3 subarray tend to decrease proportionally to the spacing and that sets of seismometers at the same spacing tend to produce uniform sample reductions in noise. This suggests that $\tilde{\rho}$ is approximately constant for a given spacing. If we assume that the normalized zero-lag cross-correlation is constant for each pair in the array, i.e.,

$$\rho = \frac{R_{k\ell}(0)}{R_{kk}(0)} \quad k,\ell = 1,\ldots,N \tag{6}$$

then, using an argument similar to that used in deriving Fisher's asymptotic z approximation (see Anderson 1958, pp.74-5) we may show that the distribution of the sample reduction approaches a normal distribution with mean

$$\mu\hat{R} = -10[\log N - \log\{1+(N-1)\rho\}] \tag{7}$$

and standard error for the case N=3

$$\sigma\hat{R} = \frac{20(1-\rho)}{\sqrt{2NBT}} \tag{8}$$

where B is the bandwidth over which the zero-lag correlations are computed and T is the sample length in seconds. Figure 2 shows the expected reduction for each value of the common theoretical noise correlation for N=3. The two reduction points of interest on the curve are for the values of ρ (as indicated experimentally) corresponding to 3-km and greater than or equal to 6-kilometer spacings. The vertical deviations are 95% confidence limits for the SDL filter with the parameters specified

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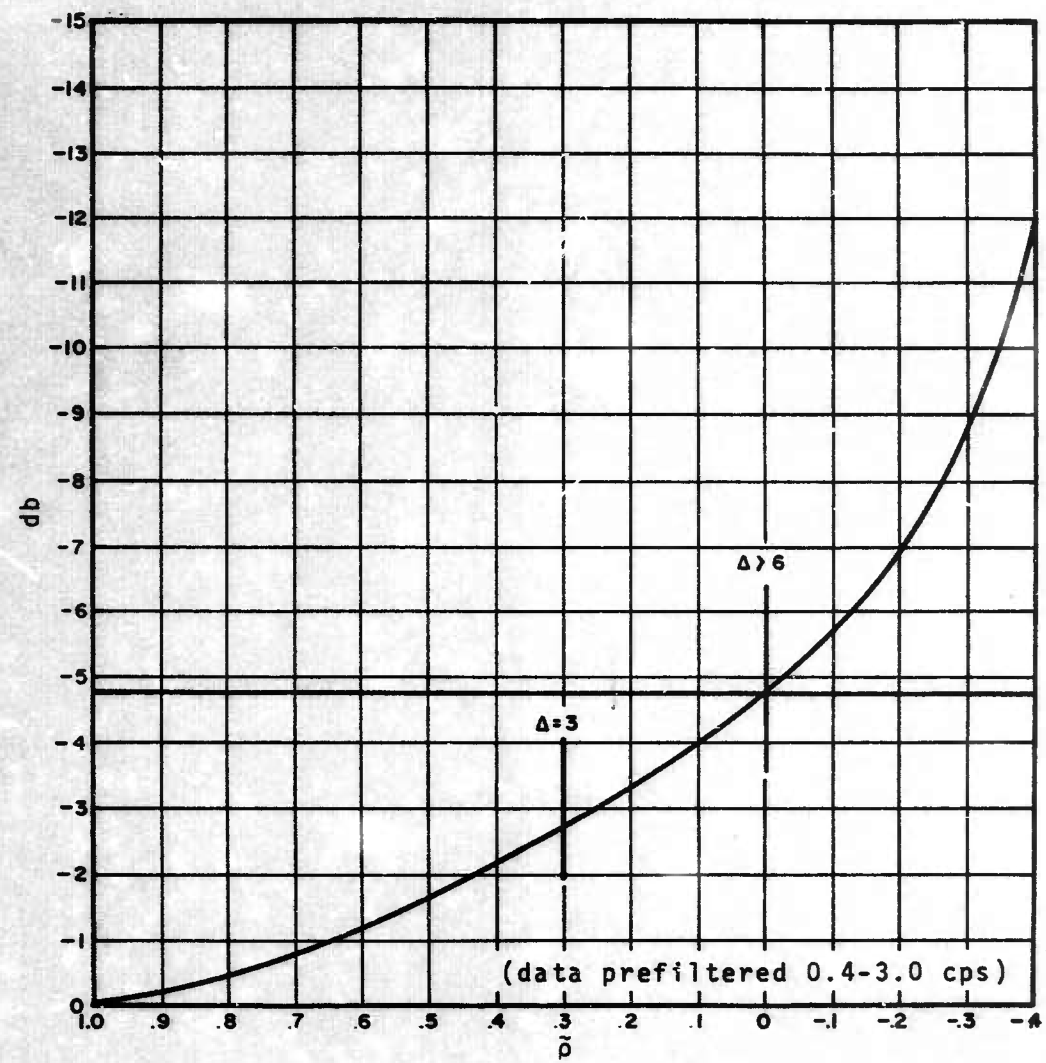

Figure 2. Noise Reduction for N=3

in the following table.

	SDL Filter (.4-3.0)	Lincoln Lab Filter (.6-2.0)
T	50 Sec	50 Sec
B	2.6 cps	1.4 cps
6BT	260	140
σR	$.715(1-\rho)$	$.985(1-\rho)$

Signal, Noise, and Signal-to-Noise Ratio

We define signal amplitude as one-half the peak-to-trough excursion, in mμ, occurring in the first eight seconds of the P signature. Noise is considered to be either the rms value, in mμ, obtained in a 50-second interval ahead of P, or noise power, in $m\mu^2$, at 1 cps, computed from a 60-second sample ahead of the P arrival. Signal-to-noise ratios are based on rms noise values. Each of the quantities signal loss, rms noise reduction, and S/N ratio improvement was computed in the following manner:

$$db = 20 \log \left(\frac{\text{value on the beamformed output trace}}{\text{average value from traces in the beam}}\right)$$

and noise power reduction at 1 cps was determined by

$$db = 10 \log \left(\frac{\text{noise power on the beamformed output trace}}{\text{average noise power on input traces}}\right)$$

Finally, in those cases where noise reduction was computed in terms of the zero-lag autocorrelation and cross-correlations, we used the following formula:

$$db = -10 \left[\log N - \log\{1+(N-1)\tilde{\rho}\}\right]$$

As we pointed out earlier, values obtained for N=6 are averages over seven events, whereas values based on the 17 March 1967 recordings for N=3 are averages of either 2 or 6 beams representing different combinations of outputs from sensors at a given spacing.

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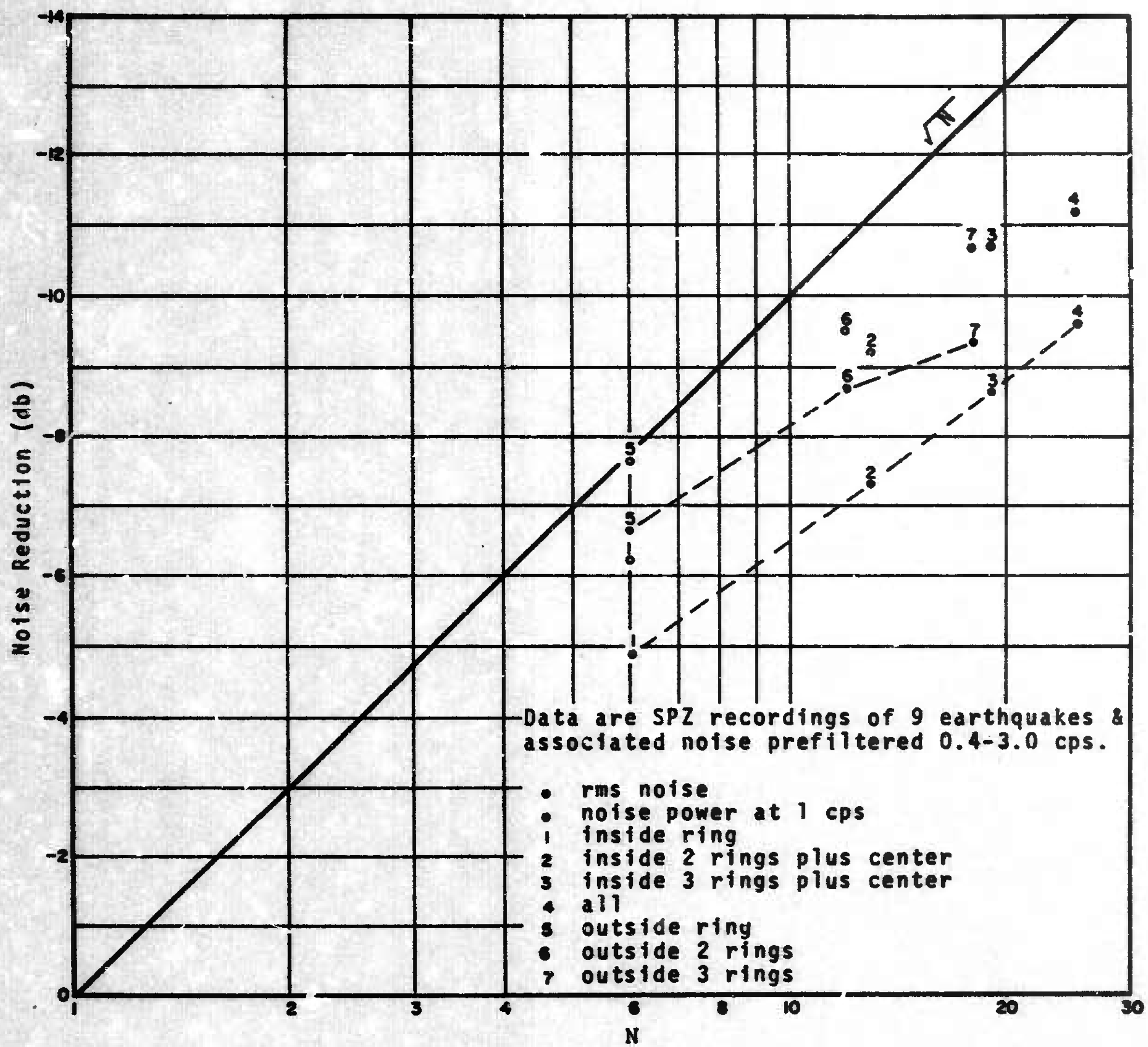

Figure 3. Average Noise Reduction by Beamforming Outputs of the Extended E3 Subarray

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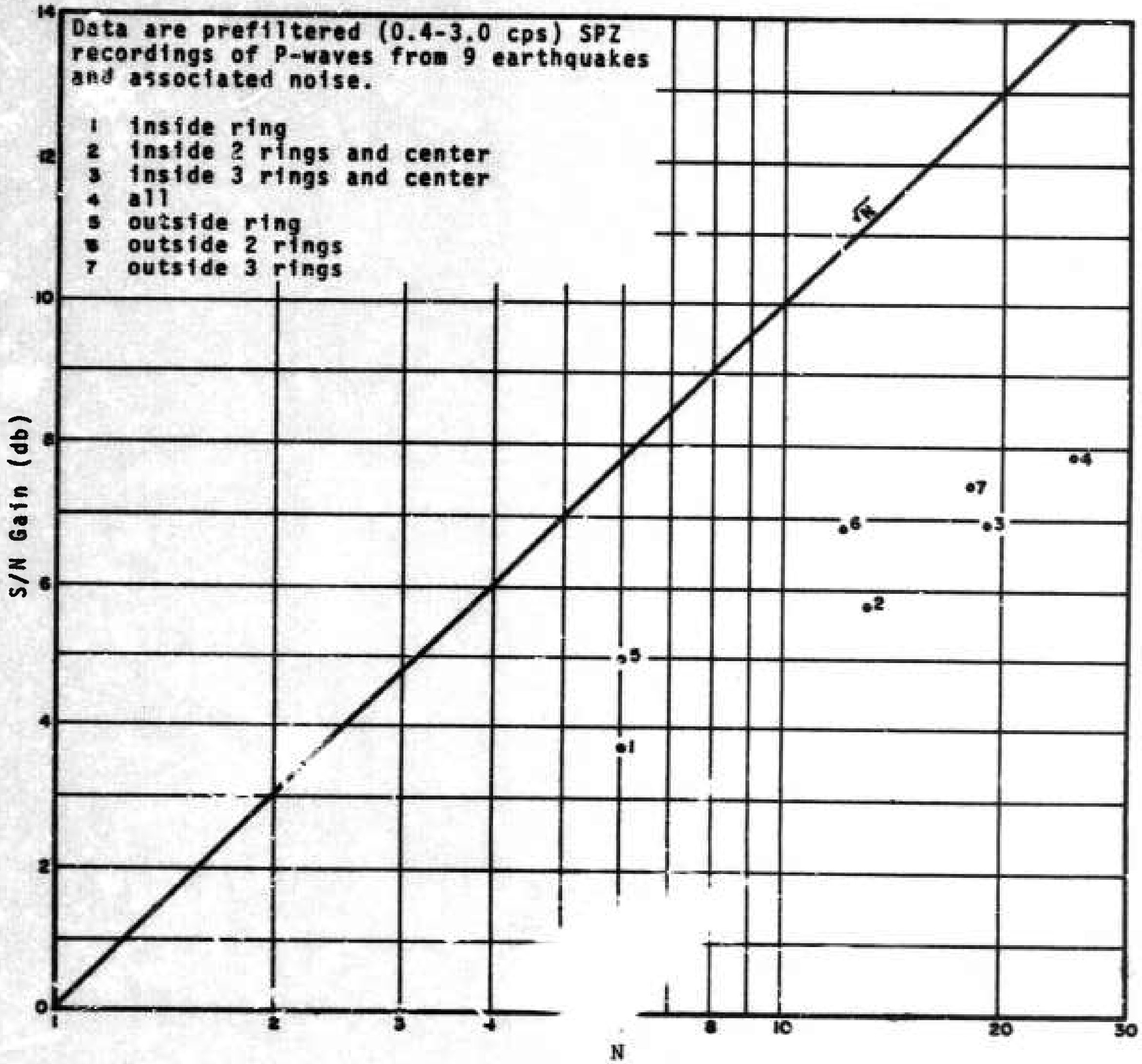

Figure 4. Average S/N Gain by Beamforming Outputs from the Extended E3 Subarray

RESULTS

In this section we first present results pertinent to the effectiveness of beamsteering outputs from the extended E3 subarray (Figures 3, 4, 5, and 6), and then extend the discussion to consider the effect of inter-sensor spacing on short-period beamforming results (Figures 7 and 8).

Figure 3 is a plot of noise reduction, either rms or power at 1 cps, as a function of N. The figure illustrates four significant points: first, $N^{\frac{1}{2}}$ reduction is obtained for noise power at 1 cps only in the case of N=6 (the outer ring); second, the reduction of rms noise levels never quite reached $N^{\frac{1}{2}}$; third, noise reduction is less favorable, relative to $N^{\frac{1}{2}}$, for greater N; and fourth, beams made of outputs from the outer ring(s) yield more noise reduction than those consisting of traces recorded in the inner ring(s). The last result is explained by the fact that inter-sensor spacing tends to be greater on the outside rings, and the noise is therefore less correlated between adjacent sensors.

Figure 4 shows average S/N gain as a function of N. Here we see immediately that $N^{\frac{1}{2}}$ enhancement is never achieved, due largely to the fact the rms noise reduction falls short of $N^{\frac{1}{2}}$ as shown by Figure 3, and partly because 1-2 db of signal is lost in the beamforming process. We further note that enhancement is less favorable relative to $N^{\frac{1}{2}}$ for larger N, and that the outer ring(s) yield better results than the inner ring(s).

Figures 5 and 6 show noise reduction and S/N enhancement versus sensor spacing for N=6. In this case beams were formed using outputs from individual rings so that values plotted at Δ = 3 km correspond to data recorded on the inside ring, Δ = 6 the second ring, Δ=8 the third ring, and

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Data are SPZ recordings of 7
earthquakes & associated noise
prefiltered 0.4-3.0 cps.

N=6
• rms noise
• noise power at 1 cps
1 inside ring
2 second ring
3 third ring
4 outside ring

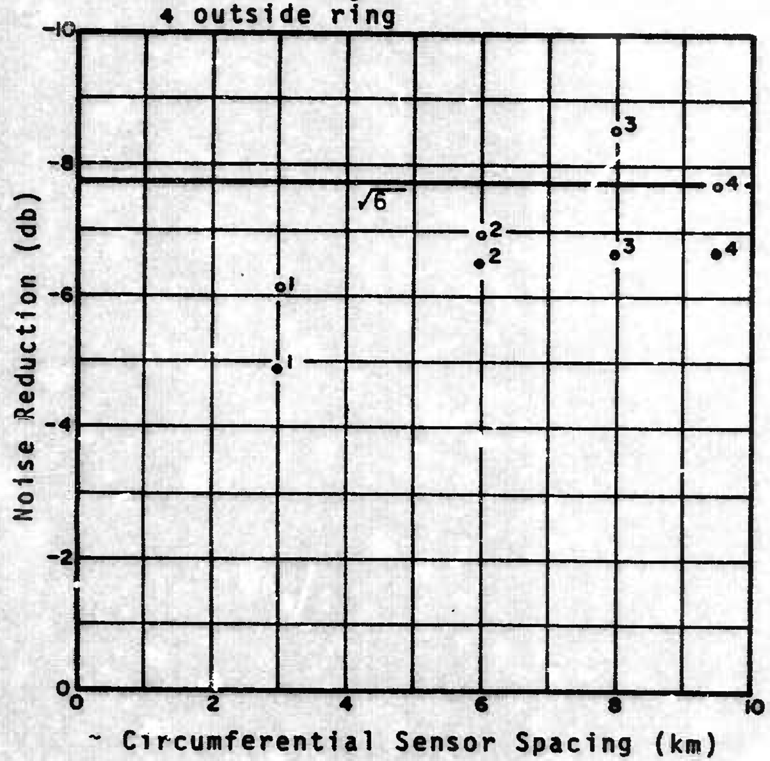

Figure 5. Average Noise Reduction by Beamforming Six Outputs of the Extended E3 Subarray

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Data are SPZ recordings of 7 earthquakes & associated noise prefiltered 0.4-3.0 cps.
N= number of outputs summed = 6

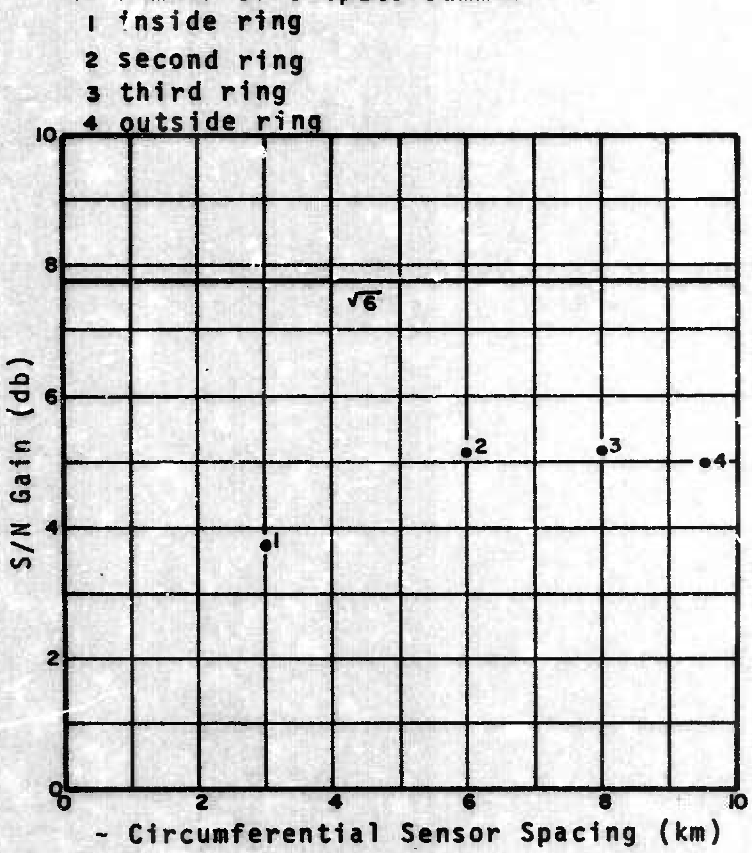

Figure 6. Average S/N Gain by Beamforming Six Outputs of the Extended E3 Subarray

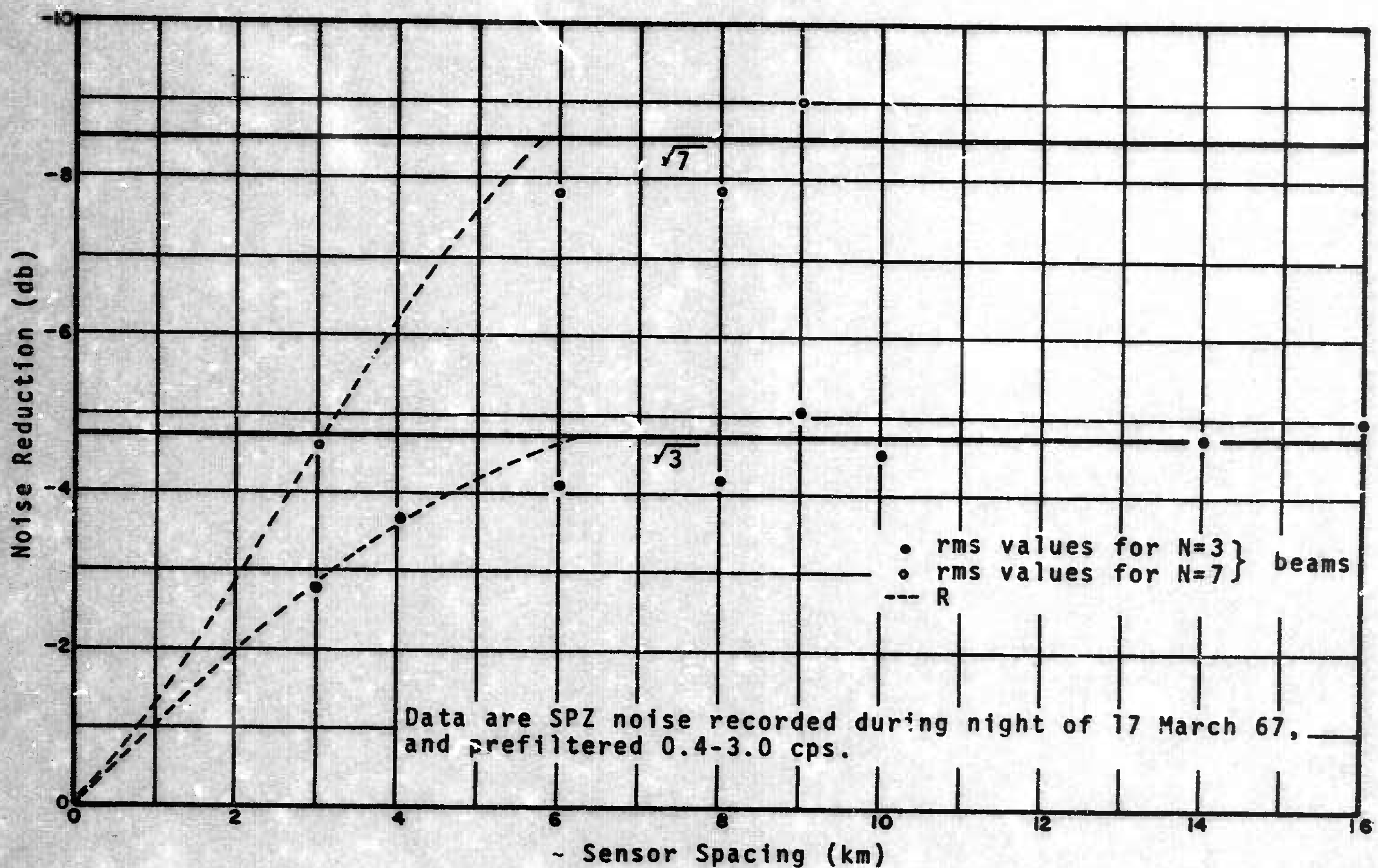

Figure 7. Average Noise Reduction in the Extended E3 Subarray for Two Experimental Methods

Δ = 9.5 km the outside ring; these spacings could more appropriately be called "minimum" intervals. As shown in Figure 5, noise power at 1 cps is reduced by $N^{\frac{1}{2}}$ in the Δ interval 6-8 kilometers, and rms noise is reduced to within 1 db of $N^{\frac{1}{2}}$ at Δ = 6 and remains reasonable constant thereafter. On the other hand, S/N enhancement (Figure 6) reaches a maximum, + 5 db, at Δ = 6 and remains essentially constant beyond. Once again we are reminded that imprecision in the beamforming process accounts for 1-2 db signal loss.

We turn now to examples of beamforming in which N has been held constant and spacing between adjacent sensors has been changed from a minimum of 3 km to a maximum of 16 km (Figures 7 and 8). Data plotted on Figure 7 were prefiltered to 0.4-3.0 cps, while those shown in Figure 8 were bandlimited in the range 0.6-2.0 cps. In both figures the dashed curves represent results for noise reduction based in part on the average of the noise mean squares (equation 2), whereas the plotted points are based on the average rms value input to the beam. Referring to Figure 7, we note that the minimum sensor spacing indicated by either experimental method for N=3 or N=7 is about 6 km, if $N^{\frac{1}{2}}$ noise reduction is desired. Actually, values based on average rms reach $N^{\frac{1}{2}}$ reduction at 8 or 9 km. It is important to remember that the plotted data for N=3 are really averages of either two or six beams, whereas, each plot for N=7 was taken from a single beam. As shown in Figure 8, the minimum spacing indicated for data prefiltered 0.6-2 cps is about 5 km, and rms values reach $N^{\frac{1}{2}}$ at about 8 km spacing.

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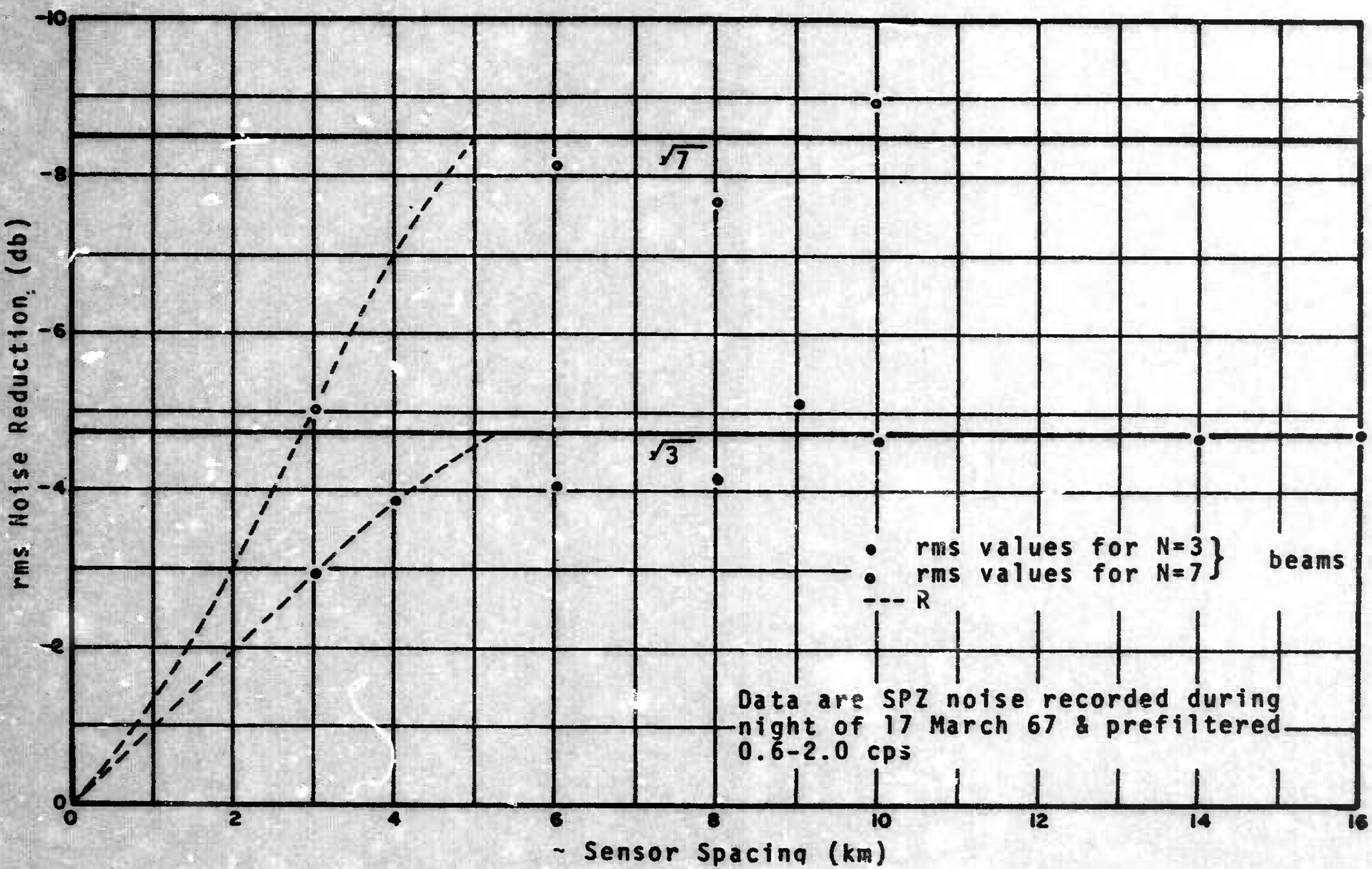

Figure 8. Average Noise Reduction in the Extended E3 Subarray for Two Experimental Methods

CONCLUSIONS

The following conclusions are based on the results of a beamforming study which used short-period vertical-component seismograms recorded during January-March 1967 in the extended E3 subarray at the Montana LASA. With the exception of beams made up of seven inputs, our results represent averages taken from several beams.

1. Beams consisting of prefiltered (0.4-3.0 cps) inputs from the entire extended E3 subarray do not yield $N^{1/2}$ improvement in signal-to-noise ratio. This is due primarily to the fact that noise is partly correlated between adjacent sensors and therefore is not reduced by as much as $N^{1/2}$, and partly to signal losses accompanying the beamforming process.

2. If input data are prefiltered to 0.4-3.0 cps, beams composed of six traces reduce noise by approximately $N^{1/2}$ when element spacings are equal to or greater than 6 kilometers.

3. For data prefiltered 0.4-3.0 cps, beams consisting of either 3 or 7 inputs reduce the average of the noise mean squares and average rms noise approximately by $N^{1/2}$ at a minimum sensor separation equal to or greater than 6 kilometers. If the data are prefiltered 0.6-2.0 cps, the minimum spacing is reduced to about 5 kilometers.

4. Average signal loss due to imprecise beams amounts to 1-2 db.

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) TELEDYNE, INC. ALEXANDRIA, VIRGINIA	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP ---

3. REPORT TITLE
A BEAMFORMING STUDY USING OUTPUTS FROM THE EXTENDED E3 SUBARRAY AT THE MONTANA LASA

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Scientific

5. AUTHOR(S) (Last name, first name, initial)
Hartenberger, R. A. and Shumway, R. H.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
11 September 1967	24	3

8a. CONTRACT OR GRANT NO. F 33657-67-C-1313 b. PROJECT NO. VELA T/6702 c. ARPA Order No. 624 d. ARPA Program Code No. 5810	9a. ORIGINATOR'S REPORT NUMBER(S) 198 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) ---

10. AVAILABILITY/LIMITATION NOTICES
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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
---	ADVANCED RESEARCH PROJECTS AGENCY Nuclear Test Detection Office Washington, D. C.

13. ABSTRACT

Short-period seismograms representing nine teleseismic earthquakes recorded by vertical component instruments in the extended E3 subarray at the Montana LASA were bandpass-filtered and beam-formed to determine the effect on average input signal-to-noise ratio, signal, and noise.

Results of the study show that beamsteering all 25 outputs (prefiltered 0.4-3.0 cps) from the extended E3 subarray fails to improve the signal-to-noise by the square root of N, where N is the number of inputs to the beams. This is due partly to the fact that noise is in some measure correlated between the more closely spaced sensors and therefore is not reduced by $N^{\frac{1}{2}}$, and partly to signal losses (1-2 db) accompanying the beam-forming process.

The analysis further indicates that beams consisting of 3, 6, and 7 input traces prefiltered 0.4-3.0 cps reduce rms noise levels at the subarray by approximately $N^{\frac{1}{2}}$ at a minimum inter-sensor spacing equal to or greater than 6 kilometers. Finally, if the input data are prefiltered to the band 0.6-2.0 cps, the minimum spacing for $N^{\frac{1}{2}}$ noise reduction is decreased to about 5 kilometers.

DD FORM 1 JAN 64 1473

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14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Beamforming						
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